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Nonfactorization and Color-Suppressed $B \to \psi(\psi(2S)) + K(K^*)$ Decays

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Abstract

Using $N_c = 3$ value of the parameter $a_2 = 0.09$ but including a modest nonfactorized amplitude, we show that it is possible to understand all data, including polarization, for color-suppressed $B \to \psi(\psi(2S)) + K(K^*)$ decays in all commonly used models of form factors. We show that for $B \to \psi + K$ decay one can define an effective a_2, which is process-dependent and, in general, complex; but it is not possible to define an effective a_2 for $B \to \psi + K^*$ decay. We also explain why nonfactorized amplitudes do not play a significant role in color-favored B decays.

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It was shown, in ref. [1], that within the factorization approximation, the commonly used models for $B \to K(K^*)$ transition form factors failed to account simultaneously for the following two measured ratios,

$$R \equiv \frac{\Gamma(B \to \psi K^*)}{\Gamma(B \to \psi K)},$$
$$P_L \equiv \frac{\Gamma_L(B \to \psi K^*)}{\Gamma(B \to \psi K^*)}. \tag{1}$$

In this note, we have relaxed the factorization approximation to allow nonfactorized contributions to the decay amplitudes and demonstrated that all the commonly used models for the transition form factors can be consistent not only with the quantities R and P_L of eqn. (1) but also with the following three quantities [2]

$$R' \equiv \frac{\Gamma(B \to \psi K)}{\Gamma(B \to \psi' K)},$$
$$R'' \equiv \frac{\Gamma(B \to \psi K^*)}{\Gamma(B \to \psi' K^*)}, \tag{2}$$

and the measured value of $B(B \to \psi K)$ [3, 4]. Here ψ' is $\psi(2S)$.

We begin with some definitions relevant to the analysis of $B \to \psi(\psi') + K(K^*)$. The relevant part of the weak Hamiltonian for $b \to c\bar{c}s$ decay is

[5],

$$H_w = \frac{G_F}{\sqrt{2}} V_{cb} V_{cs}^* \left\{ C_1(\bar{c}b)(\bar{s}c) + C_2(\bar{c}c)(\bar{s}b) \right\}. \tag{3}$$

Here $(\bar{c}b)$ etc. represent color-singlet (V-A) brackets and C_1 and C_2 are the Wilson coefficients for which several values can be found in the literature: $C_1 = 1.12$, $C_2 = -0.26$ [5, 6]; $C_1 = 1.13$, $C_2 = -0.29$ [7]. We adopt the values, $C_1 = 1.12 \pm 0.01$, $C_2 = -0.27 \pm 0.03$. Fierz-transforming the color-singlet combinations in eqn. (3) in color space, we obtain, with number of colors $N_c = 3$,

$$(\bar{c}b)(\bar{s}c) = \frac{1}{3}(\bar{c}c)(\bar{s}b) + \frac{1}{2}\sum_{a=1}^{8} (\bar{c}\lambda^a b)(\bar{s}\lambda^a c), \tag{4}$$

where λ^a are the Gell-Mann matrices. $\frac{1}{2}\sum(\bar{c}\lambda^a b)(\bar{s}\lambda^a c)$ ($\equiv H_w^{(8)}$) being a product of two color-octet currents contributes to the nonfactorized part of the decay amplitude.

The amplitudes for $B \to \psi K(K^*)$ decays can be written using eqns. (3) and (4) as,

$$A(B \to \psi K(K^*)) = \frac{G_F}{\sqrt{2}} V_{cb} V_{cs}^* a_2 \left[\langle \psi K(K^*) \mid (\bar{c}c)(\bar{s}b) \mid B \rangle \right. \\ \left. + \kappa \left\langle \psi K(K^*) \mid H_w^{(8)} \mid B \right\rangle \right], \tag{5}$$

where $a_2 = C_2 + C_1/3 = 0.10 \pm 0.03$ and $\kappa = C_1/a_2$. The first term in eqn. (5) can be evaluated using factorization procedure [8]. The second term accounts for the non-factorization contribution. Since κ is large, of the order of ten, even a small amount of nonfactorized contribution will have a significant effect on the amplitudes. We recognize that there could be nonfactorized contributions to the first term on the right hand side of eqn. (5), however, we anticipate the (nonfactorized) contribution of the second term to dominate due to the largeness of κ. We write the Lorentz structures of $\left\langle \psi K(K^*) \mid H_w^{(8)} \mid B \right\rangle$, for ease of comparison with the factorized amplitude, as

$$\begin{aligned} \left\langle K\psi \mid H_w^{(8)} \mid B \right\rangle &= m_\psi f_\psi (\varepsilon_1^*.p_B) F_1^{NF}(m_\psi^2), \\ \left\langle K^*\psi \mid H_w^{(8)} \mid B \right\rangle &= m_\psi f_\psi \Big[(m_B + m_{K^*})(\varepsilon_1^*.\varepsilon_2^*) A_1^{NF} \\ &- \frac{(\varepsilon_2^*.(p_B - p_{K^*}))(\varepsilon_1^*.(p_B + p_{K^*}))}{(m_B + m_{K^*})} A_2^{NF} \\ &+ \frac{2i}{(m_B + m_{K^*})} \varepsilon_1^{*\mu} \varepsilon_2^{*\nu} \varepsilon_{\mu\nu\alpha\beta} p_{K^*}^\alpha p_B^\beta V^{NF} \Big], \end{aligned} \tag{6}$$

where ε_1 and ε_2 are the polarization vectors of ψ and K^* respectively. The factorized part of the amplitude is obtained by replacing F_1^{NF}, A_1^{NF}, A_2^{NF} and V^{NF} by F_1^{BK}, $A_1^{BK^*}$, $A_2^{BK^*}$ and V^{BK^*}, the relevant form factors [8] respectively.

We make here one very plausible assumption: In $B \to \psi K^*$ decay the nonfactorizable amplitude contributes only to S-wave final states. This implies that we

retain A_1^{NF} which contributes to S-wave but neglect A_2^{NF} (D-wave) and V^{NF}(P-wave). The rationale for this assumption is that the t- and u-channel exchanges in $H_w^{(8)} + B \rightarrow \psi + K^*$ involve particles at least as heavy as the b-flavor ($\gtrsim 5$ GeV and as the momentum in the reaction is ≈ 1.5 GeV, it is hard to produce higher partial waves through four-point functions. S-waves, if allowed, would dominate. We emphasize that the factorized amplitude is immune to these arguments.

With our definition of factorized and nonfactorized amplitudes, we evaluate $A(B \rightarrow \psi(\psi') + K(K^*))$, and write the expressions for R, P_L, R', R'' and $B(B \rightarrow \psi K)$ as follows [1, 2]:

$$R = 1.082 \left[\frac{A_1^{BK^*}(m_\psi^2)}{F_1^{BK}(m_\psi^2)}\right]^2 \frac{(a\xi - bx)^2 + 2(\xi^2 + c^2y^2)}{\eta^2}, \tag{7}$$

$$P_L = \frac{(a\xi - bx)^2}{(a\xi - bx)^2 + 2(\xi^2 + c^2y^2)}, \tag{8}$$

$$R' = (4.178 \pm 0.515) \left[\frac{F_1^{BK}(m_\psi^2)}{F_1^{BK}(m_{\psi'}^2)}\right]^2 \frac{\eta^2}{\eta'^2}, \tag{9}$$

$$R'' = (1.845 \pm 0.227) \left[\frac{A_1^{BK^*}(m_\psi^2)}{A_1^{BK^*}(m_{\psi'}^2)}\right]^2 \frac{(a\xi - bx)^2 + 2(\xi^2 + c^2y^2)}{(a'\xi' - b'x')^2 + 2(\xi'^2 + c'^2y'^2)}, \tag{10}$$

$$B(B \rightarrow \psi K) = (2.63 \pm 0.19) \mid a_2 \eta F_1^{BK}(m_\psi^2) \mid^2 \%, \tag{11}$$

where,

$$\xi = 1 + \kappa \frac{A_1^{NF}(m_\psi^2)}{A_1^{BK^*}(m_\psi^2)},$$
$$\eta = 1 + \kappa \frac{F_1^{NF}(m_\psi^2)}{F_1^{BK}(m_\psi^2)},$$

$$
\begin{aligned}
x &= \frac{A_2^{BK^*}(m_\psi^2)}{A_1^{BK^*}(m_\psi^2)}, \\
y &= \frac{V^{BK^*}(m_\psi^2)}{A_1^{BK^*}(m_\psi^2)}, \\
a &= \frac{m_B^2 - m_{K^*}^2 - m_\psi^2}{2m_{K^*}m_\psi}, \\
b &= \frac{2 \mid \vec{p}_{\psi K^*} \mid^2 m_B^2}{m_{K^*}m_\psi \left(m_B + m_{K^*}\right)^2}, \\
c &= \frac{2 \mid \vec{p}_{\psi K^*} \mid m_B}{\left(m_B + m_{K^*}\right)^2}.
\end{aligned} \tag{12}
$$

The primed quantities in eqns. (9) and (10) are obtained from the unprimed ones by replacing ψ with ψ'. We have used $V_{cb} = 0.04$ and $\tau_B = 1.5 \times 10^{-12} s$ [4] in determining eqn. (11). We have also used [5]: $f_\psi = (384 \pm 14)$ MeV and $f_{\psi'} = (282 \pm 14)$ MeV. The errors in eqns. (9), (10) and (11) reflect the errors in f_ψ and $f_{\psi'}$.

It is evident from the above (see eqn. (11)) that for $B \to \psi K$ decay, involving a single Lorentz scalar, it is possible to define an effective a_2, $a_2^{eff} = a_2 \eta$; however, it is not possible to define an effective a_2 for $B \to \psi K^*$ as this amplitude involves three independent Lorentz scalars.

Now, to the experimental data. For the ratio R we use [1, 3],

$$
R_{expt} = 1.71 \pm 0.34. \tag{13}
$$

For P_L we take the weighted average of three measurements: $0.80 \pm 0.08 \pm 0.05$ [3], $0.66 \pm 0.10^{+0.10}_{-0.08}$ [9] and $0.97 \pm 0.16 \pm 0.15$ [10],

$$
P_L = 0.78 \pm 0.07. \tag{14}
$$

From ref. [4] we calculate,

$$
\begin{aligned}
R'_{expt} &= 1.48 \pm 0.46, \\
R''_{expt} &= 1.13 \pm 0.50.
\end{aligned} \tag{15}
$$

We emphasize that the error assignments are ours, where we have reduced the propagated error by one-third assuming that some of the systematic errors would cancel in the ratio. For $B(B \to \psi K)$ we use the weighted average of $B(B^+ \to \psi K^+)$ and $B(B^0 \to \psi K^0)$ [4],

$$B(B \to \psi K) = (0.094 \pm 0.012)\%. \tag{16}$$

In our description there are four parameters, ξ, η, ξ' and η'. Eventually, we reduce them to three by a particular choice of eqn. (17) in the following. x and y are not free parameters; rather their allowed range is determined by the experimental value of P_L as detailed below.

In Fig. (1) we have plotted the range of the ratios x and y (see eqn. (12)) allowed by the polarization data of eqn. (14) for different values of χ $(= A_1^{NF}(m_\psi^2)/A_1^{BK^*}(m_\psi^2))$ and the values of C_1 and C_2 (equivalently a_1 and a_2) shown in the figure caption. We note that the predictions of all the models considered in ref. [1] become consistent with the polarization data with $\chi \approx 0.12$, a value which is eminently plausible.

Next, we calculate P_L, R, R' and R'' and $B(B \to \psi K)$ in six representative models (see ref. [1] for details): BSWI [8], where all form factors are calculated at $q^2 = 0$ and extrapolated with monopole forms; BSWII [1, 5], where $A_1^{BK^*}$ has a monopole extrapolation but F_1^{BK}, A_2^{BK} and V^{BK^*} have dipole behavior; CDDFGN [11], where the heavy to light transition form factors are calculated at zero recoil and extrapolated with monopole forms; HSQ [12], where the strange quark is treated as heavy and the form factors are extrapolated from $q^2 = q^2_{max}$ to m_ψ^2 by the method described in ref. [5]; JW [13], where the form factors are calculated at $q^2 = 0$ in a light-front formalism and extrapolated to m_ψ^2 using a particular two-parameter formula; and IW scheme [1, 14] where form factors measured in $D \to K(K^*)$ semileptonic decays are continued to $B \to K(K^*)$ transitions. We wish to emphasize that the "experimental" determination of the form factors in $D \to K(K^*)$ transitions are not

model-free as a monopole assumption is made for all form factors.

In Table (1) we have shown a sampling of successful predictions for all the measured quantities in these models. In this Table we have introduced a parameter r defined by

$$\begin{aligned} r &\equiv \frac{F_1^{NF}(m_{\psi'}^2)}{F_1^{NF}(m_{\psi}^2)} \frac{F_1^{BK}(m_{\psi}^2)}{F_1^{BK}(m_{\psi'}^2)}, \\ &= \frac{A_1^{NF}(m_{\psi'}^2)}{A_1^{NF}(m_{\psi}^2)} \frac{A_1^{BK^*}(m_{\psi}^2)}{A_1^{BK^*}(m_{\psi'}^2)}. \end{aligned} \tag{17}$$

There is no compelling reason for the equality in eqn. (17); one could have chosen independent ratios for $B \to \psi(\psi') + K$ and $B \to \psi(\psi') + K^*$ decays and described the data equally well.

Clearly, all data for color-suppressed decays, $B \to \psi(\psi') + K(K^*)$, can be accounted for in all models by using the "standard" $N_c = 3$ value for $a_2(= 0.09)$ but with the inclusion of a modest nonfactorized contribution to the amplitude with the appropriate Lorentz structure accompanying F_1^{BK} in $B \to \psi K$ and $A_1^{BK^*}$ in $B \to \psi K^*$. In this regard we differ from the proposal by Carlson and Milana [15] who assume that nonfactorized contributions effect Γ_T only and not Γ_L. In our language it would mean $A_1^{NF} = A_2^{NF} = 0$, $V^{NF} \neq 0$. Our suggestion, $A_1^{NF} \neq 0$, $A_2^{NF} = V^{NF} = 0$, effects both Γ_T and Γ_L.

Finally, we show why factorization assumption works so well for all models in explaining the polarization data in color-favored decays. The amplitude (analogous to eqn. (5)) for $\bar{B}^0 \to D^{*+} + \rho^-$ decay can be written as

$$\begin{aligned} A(\bar{B}^0 \to D^{*+}\rho^-) = \frac{G_F}{\sqrt{2}} V_{cb} V_{ud}^* a_1 & \left[\left\langle D^{*+}\rho^- \mid (\bar{c}b)(\bar{d}u) \mid \bar{B}^0 \right\rangle \right. \\ & \left. + \zeta \left\langle D^{*+}\rho^- \mid \tilde{H}_w^{(8)} \mid \bar{B}^0 \right\rangle \right], \end{aligned} \tag{18}$$

where $a_1 = C_1 + C_2/3 = 1.03 \pm 0.014$ and $\zeta = C_2/a_1$ and $\tilde{H}_w^{(8)} = \frac{1}{2} \sum (\bar{c}\lambda^a u)\ (\bar{d}\lambda^a b)$. Now, since $|\zeta| \approx \kappa/40$, it is clear that the role of the nonfactorized terms is strongly

Table 1: Model predictions, with nonfactorized contribution, for P_L, R, R', R'' and $B(B \to \psi K)$; $C_1 = 1.11$ and $C_2 = -0.28$, or, equivalently $a_1 = 1.02$ and $a_2 = 0.09$. Read R' and R'' with a 12.3% error and BR with a 7.3% error.

Model	$\frac{A_1^{NF}}{A_1^{BK*}}$	$\frac{F_1^{NF}}{F_1^{BK}}$	r	P_L	R	R'	R''	$BR^{(a)}$ in %
BSWI	0.07	0.23	1.30	0.74	1.48	1.79	1.55	0.094
	0.07	0.23	1.40	0.74	1.48	1.59	1.42	0.094
BSWII	0.10	0.13	1.20	0.71	1.98	1.35	1.65	0.095
	0.10	0.13	1.30	0.71	1.98	1.21	1.46	0.095
CDDFGN	0.15	0.16	1.30	0.75	1.44	1.86	1.54	0.099
	0.15	0.16	1.40	0.75	1.44	1.67	1.38	0.099
HSQ	0.09	0.30	1.30	0.72	1.97	1.26	1.50	0.093
	0.09	0.30	1.40	0.72	1.97	1.11	1.36	0.093
JW	0.07	0.23	1.30	0.74	1.48	1.79	1.55	0.094
	0.07	0.23	1.40	0.74	1.48	1.59	1.42	0.094
IW	0.11	0.23	1.40	0.76	1.42	1.72	1.57	0.094
	0.11	0.23	1.50	0.76	1.42	1.54	1.43	0.094
Expt.				0.78 ± 0.07	1.71 ± 0.34	1.48 ± 0.46 (b)	1.13 ± 0.50 (b)	0.094 ± 0.012

(a) BR $\equiv$ B($B \to \psi K$), (b) Our estimate of error.

suppressed compared to the case of color-suppressed decays. As a consequence, factorization assumption works well for color-favored decays. Thus assuming factorization, $P_L(\bar{B}^0 \to D^{*+}\rho^-)$ is given by

$$P_L(\bar{B}^0 \to D^{*+}\rho^-) = \frac{(\hat{a} - \hat{b}\hat{x})^2}{(\hat{a} - \hat{b}\hat{x})^2 + 2(1 + \hat{c}^2\hat{y}^2)}, \tag{19}$$

where the hatted quantities relevant to $\bar{B}^0 \to D^{*+}\rho^-$ decay are the analogues of the unhatted ones defined in eqn. (12). Numerically $\hat{a}$ is twice as large as $\hat{b}$ and much larger than $\hat{c}$: $\hat{a} = 7.507$, $\hat{b} = 3.225$ and $\hat{c} = 0.433$. Thus for $\hat{x} \approx 1$ and $\hat{y} \approx (1 - 2)$, which most models predict, the longitudinal polarization is close to unity, in agreement with data [3].

We wish to emphasize an important difference between F_1^{BK}, $A_1^{BK^*}$ and F_1^{NF}, A_1^{NF}: Whereas the former, being form factors, are three-point functions and real at $q^2 = m_\psi^2$, the latter representing the scattering of the weak spurion, $H_w^{(8)}$, $H_w^{(8)} + B \to \psi + K(K^*)$ are four-point functions. F_1^{NF} and A_1^{NF} are needed at the Mandelstam variables $s = m_B^2$, $t = m_\psi^2$, $u = m_{K(K^*)}^2$. *In general, F_1^{NF} will be complex since $m_B > (m_\psi + m_K)$.*

In summary, we have proposed that nonfactorized amplitudes play a crucial role in color-suppressed $B \to \psi(\psi') + K(K^*)$ decays. With the additional assumption that the nonfactorized amplitude contribute only to S-wave production in $B \to \psi(\psi')K^*$ decay, we have demonstrated that all data on $B \to \psi(\psi') + K(K^*)$ can be accommodated in the commonly used form factor models with the inclusion of a modest nonfactorized contribution. We emphasize that without the nonfactorized contribution, polarization data in $B \to \psi K^*$ decay cannot be understood [1].

For $B \to \psi K$ decay one can indeed define an effective a_2, which could be complex as F_1^{NF} would, in general, be complex. This effective a_2 is also process-dependent. Despite the "standard" $N_c = 3$ value of a_2 being 0.10 ± 0.03, since $\kappa = C_1/a_2$ is of

the order of ten, the effective a_2 could be ≈ 0.22 even for a modest nonfactorized contribution of 10% in the amplitude. For more complex processes involving more than one form factor such as $B \to \psi K^*$ it is not possible to factor out an effective a_2.

A corollary to our analysis is that the effective

a_2 being process-dependent, there is no reason for it to be the same in color-suppressed $B \to \pi(\rho) + D(D^*)$ decays as in $B \to \psi + K(K^*)$ decays.

Nonfactorized contributions in charmed meson decays were first discussed by Deshpande, Gronau and Sutherland [16]. More recently, Cheng [17], Cheng and Tseng [18] and Soares [19] have used language similar to ours but their emphasis was quite different. In ref. [18] the authors assume factorization to be valid and try to explain the ratios R and P_L by using modified form factors. However their predicted P_L does not satisfy eqn. (14). The role of nonfactorized contributions to D and B decays has been discussed by Blok and Shifman (ref. [6, 20] and references therein). Their emphasis was to understand the discarding of of the $1/N_c$ term in the definitions $a_{1,2} = C_{1,2} + C_{2,1}/N_c$. However, if $1/N_c$ terms are discarded a_2 would be negative, whereas recent experiments [3] leave no doubt that a_2 is positive. The prejudice that $1/N_c$ term ought to be discarded (or cancelled by by nonfactorized contributions) was carried over to B decays from the experience in D decays, and the earlier ARGUS and CLEO data [5] appeared to support it but such is not the case at present.

Finally, our choice $a_2 = 0.10 \pm 0.03$ is consistent with the values $a_2^{HV} = 0.16 \pm 0.05$ and $a_2^{DRED} = 0.15 \pm 0.05$ quoted by Buras [21] (HV for 't Hooft-Veltman and DRED for "dimensional reduction", see ref. [21] for details and references) but is inconsistent with $a_2^{NDR} = 0.20 \pm 0.05$ (NDR for "naive dimensional reduction").

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Figure Captions

Fig.1: The domain of (x, y) allowed by the polarization data (eqn. (14)) for $B \to \psi K^*$ with different value of $\chi(\equiv A_1^{NF}(m_\psi^2)/A_1^{BK^*}(m_\psi^2))$; $C_1 = 1.11$ and $C_2 = -0.28$, or, equivalently $a_1 = 1.02$ and $a_2 = 0.09$. Also shown are predictions of various models, A: BSWI, B: BSWII, C: CDDFGN, D: HSQ, E: JW and F: IW.

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